

# 657. Tribological properties of cast iron conditioned by a technological surface layer and material microstructure

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**Abstract.** The article presents test results of a surface layer of cast iron after subjecting it to grinding and pressure rolling at a variable burnishing force of  $P = 1000 - 4000$  N. The surface roughness, bearing surface, strengthening and stress in the surface layer as well as the microstructure of tested cast irons were determined. The following cast irons were selected for the tests: spheroidal pearlitic EN-GJSP, spheroidal ferritic EN-GJSF, and grey ferritic and pearlitic EN-GJLFP. Experimental study revealed that the surface layer after burnishing had favorable indicators of surface geometric structure and physical properties compared with the surface layer obtained after grinding. After the processes of burnishing and grinding, tribological tests were conducted. They indicate that the surface layer formed in the process of burnishing contributes to the reduction of the friction coefficient and wear. It was demonstrated that the wear process is affected by burnishing force, microstructure and the form of graphite.

**Keywords:** cast iron, surface layer, grinding, pressure rolling, friction coefficient.

## 1. Introduction

The durability and reliability of machines and devices largely depend upon friction wear resistance determined by the condition of the surface layer of the elements forming the friction pair. Hence, the selection of finishing method and parameters that determine the condition of the surface layer become increasingly important.

One of widely used methods of increasing operational properties of machine parts is surfacing called burnishing. A roller or a ball can be a tool in the process of static burnishing. When the roller is used, the pressure force is lower than the pressure force used to roll one ball. Burnishing treatment results in reduced surface roughness [13, 14]. These articles discuss the results of tests on the static burnishing of surfaces on a milling machine. By using this method, a surface roughness of  $R_a \sim 0.2 \mu\text{m}$  and an efficiency ratio of burnishing over 80% were obtained. Article [15] presents the results of the tests with one ball pressed down hydrostatically and subjected to ultrasonic vibrations with a frequency of 20 Hz. As a result of this method, a favorable state of stress in the surface layer and the change of surface roughness from  $R_a \sim 0.1 \mu\text{m}$  to tens of  $\mu\text{m}$  were obtained. The effect of burnishing [2] resulted in improved fatigue resistance of burnished elements.

There are numerous scientific studies (e. g. [2, 3, 10]) on the process of burnishing structural steels, but there are no comprehensive scientific studies on the cold work surface treatment of cast iron.

Cast iron is a typical alloy of multi-phase construction in which microstructural features determine its mechanical properties. These properties include the type of the metallic matrix and the form of graphite inclusions. Both the nature of the metallic matrix and the form of graphite significantly affect the state of the surface layer after burnishing as shown in the tests presented in [6, 8].

Cast iron is a material widely used in the machine tool industry (beds, machine bodies, gear wheels), in the automotive and tractor industry (cylinder liners, pistons, crankshafts, pins, bushings), and in the construction industry (machine gears, liners of bolt connections).

Therefore, it is justifiable to carry out research on cast iron burnishing and its effect on tribological properties.

## 2. Experiment

### 2.1. Experimental method

Roller burnishing was carried out using a device of custom design mounted on a centre lathe. A diagram of rolling is illustrated in Fig. 1.

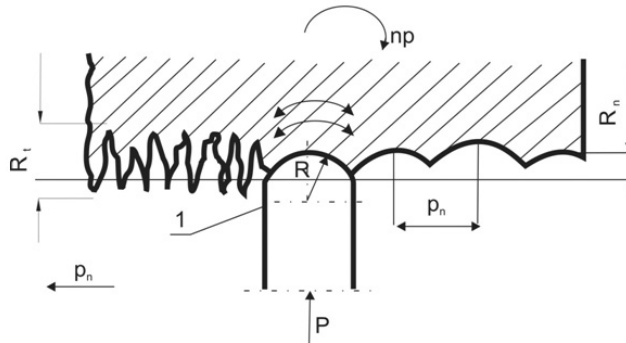


Fig. 1. Rolling diagram

Pressure rolling (Fig. 1) is a static burnishing process, in which the burnishing force is constant and it acts on the object through a disk that is in constant contact with the treated surface during the process.

The burnishing process was carried out using the following technological parameters: burnishing force  $P$  was 1000 N, 3000 N and 4000 N, burnishing feed  $f_n = 0.21$  mm/r., peripheral speed of burnished element  $v_p = 56$  m/min, the number of working passes  $i = 1$ .

For comparative purposes, grinding treatment was selected using the following conditions: grinding wheel NSAa 340 (SiC,  $L$  hardness, structure 5, grain 40/36), the grinding wheel cutting speed  $v_s = 1.59$  m/min., treated object speed  $v_p = 20$  m/min., number of passes  $i = 7$ , feed  $f = 0.005$  mm/double jump.

### 2.2. Tools for burnishing

The following tool was used for the tests: tool material 210Cr12 of Rockwell hardness 60 HRC, surface roughness  $Ra = 0.12$   $\mu$ m, disk diameter  $D = 60$  mm, and disk radius  $R = 20$  mm.

### 2.3. Material selected for the tests

Three types of cast iron (samples) were selected for the tests: spheroidal pearlitic EN-GJSP, spheroidal ferritic EN-GJSF, and grey ferritic-pearlitic EN-GJLFP. The tested materials had different metallic matrices - ferritic and pearlitic Fe<sub>55</sub> P<sub>45</sub> for EN-GJLFP cast iron, pearlitic-P<sub>92</sub> Fe<sub>8</sub> for EN-GJSP cast iron, and ferritic Fe<sub>94</sub> P<sub>6</sub> for EN-GJSF cast iron. The composition and mechanical properties of the tested cast irons are presented in Table 1. The above cast irons were burnished with forces  $P = 1000$  N, 2000 N, 3000 N, 4000 N. The anti-sample was CuSi<sub>3</sub>Zn<sub>3</sub>Mn<sub>1</sub> bronze of hardness HB90 and surface roughness  $Ra = 0.23$   $\mu$ m. In the tribological process, machine oil (kinematic viscosity at 40°C is 16.5 mm<sup>2</sup>/s, viscosity index is 60) was used as lubricant.

## 2.4. Surface analysis

Profilographometers TR-200 and PGM-1C were used to determine surface roughness, and the percentage of linear bearing surface.

**Table 1.** Chemical composition and mechanical properties of EN-GJLFP, EN-GJSP and EN-GJSF

Material	Chemical composition [%]					HB	R <sub>m</sub>
	C	Mn	Si	P	S	-	[MPa]
EN-GJLFP	3,35	0,92	2,95	0,16	0,050	215	274
EN-GJSP	3,40	0,40	2,57	0,11	0,025	310	667
EN-GJSF	3,15	0,51	3,47	0,10	0,100	210	436

The strengthening of the surface layer was tested by means of a Zwick ZHV 10 microhardness meter on the microsections of oblique samples at the angle of 0.31 - 0.35 rd polished and etched with 2% alcohol solution of HNO<sub>3</sub>.

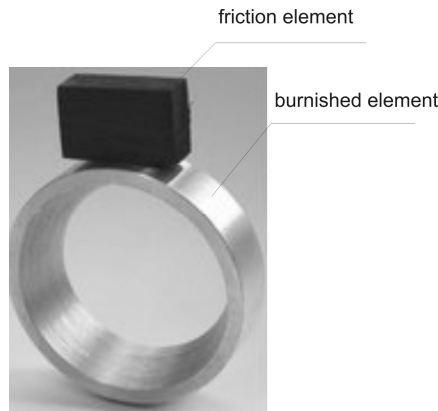
The microhardness of the basic structural components of cast iron matrix was measured with a Vickers indenter at a load of 0.1 daN.

The residual stresses of the surface layer of type I ( $\delta_1 + \delta_2$ ) were measured by an X-ray method  $\sin^2\Psi$  [3], using a "TUR-M61" diffractometer, equipped with a "GM" detector, proportional integrator, a compensating recorder and electron pulse calculator. A lamp with a chrome anticathode was used during the measurements.

The stress tests were conducted on  $\phi$  40x30 samples. In order to designate stress distribution in depth, the samples were etched chemically to suitable depths in a water solution of nitric acid. The solution concentration was 5 and 20%. A lower concentration was used to etch the samples to the depth of up to 110  $\mu$ m, while a 20% concentration was used to etch them to greater depths. The depth of etching was measured with a probe graduated at 2  $\mu$ m.

## 2.5. Tribological experiment

The tribological experiment was conducted on an AMSLER working station of type 135 in accordance with PN-75/M.-04305. The friction pair (Fig. 2) consisted of cast iron samples (disk) EN-GJL FP, EN-GJS P, EN-GJS F, which were burnished with forces  $P = 1000$  N, 3000 N, 4000 N. Silicon bronze CuSi3Zn3Mn1 (a block) was the anti-sample. After preliminary tests, based on the criterion of the temperature in the area of friction the following tribological test conditions were found: the friction velocity  $v = 0.419$  m/s, sliding distance  $s = 25$  133 m, unit pressure  $p = 5.17$  MPa, drip lubrication: machine oil (kinematic viscosity at 40°C 16.5 mm<sup>2</sup>/s, viscosity index 60).



**Fig. 2.** Friction pair of the experiment

### 3. Test results and analysis

Tables 2 and 3 present the results of the tests on the surface layer of tested cast irons after burnishing with variable forces  $P_1 = 1000$  N,  $P_2 = 3000$  N,  $P_3 = 4000$  N and grinding (as a comparative treatment). The tests demonstrated that for the selected cast irons, the state of the surface layer after burnishing is more favorable than after grinding (Table 2, 3, 4). They have smaller surface roughness  $R_a$ , higher gradients of bearing surface  $G_{20}$  and  $G_{50}$ , and greater strengthening  $U$ . In the case of the surface that was ground, tensile stresses were observed, while after burnishing compressive stresses appeared. It was found that the condition of the surface layer improved by increasing the burnishing force. The improvement of the surface layer is the result of progressive deformation with increasing burnishing force. According to the tests [1], force  $P = 4000$  N is the optimal force to produce a surface layer is in the most favorable state.

**Table 2.** The condition of the surface layer of cast iron EN-GJLFP after grinding and burnishing with pressure rolling

Working type	Properties of the surface layer				
	$R_a$ [ $\mu\text{m}$ ]	$G_{20}$ [%]	$G_{50}$ [%]	$U_{max}$ [%]	$(\delta_1 + \delta_2)_{max}$ [MPa]
Grinding	0,77	6	27	20	[130÷(-490)]
Burnising $P=1000$ N	0,65	15	27	27	-(280÷410)
Burnising $P=3000$ N	0,53	18	35	33	-(320÷460)
Burnising $P=4000$ N	0,48	18	40	41	-(310÷500)

**Table 3.** The condition of the surface layer of cast iron EN-GJSP after grinding and burnishing with pressure rolling

Working type	Properties of the surface layer				
	$R_a$ [ $\mu\text{m}$ ]	$G_{20}$ [%]	$G_{50}$ [%]	$U_{max}$ [%]	$(\delta_1 + \delta_2)_{max}$ [MPa]
Grinding	0,65	8	24	22	(5÷380)
Burnising $P=1000$ N	0,49	18	32	29	-(430÷680)
Burnising $P=3000$ N	0,42	22	37	32	-(480÷760)
Burnising $P=4000$ N	0,38	21	45	43	-(550÷820)

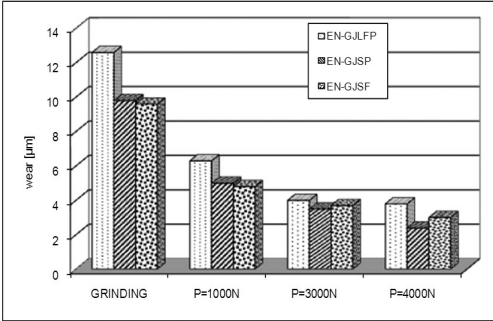
**Table 4.** The condition of the surface layer of spheroidal ferritic cast iron EN-GJSF after grinding and burnishing

Working type	Properties of the surface layer				
	$R_a$ [ $\mu\text{m}$ ]	$G_{20}$ [%]	$G_{50}$ [%]	$U$ [%]	$(\delta_1 + \delta_2)_{max}$ [MPa]
Burnishing $P = 1000$ N	0,51	14	43	5 ÷ 21	- (289 ÷ 667)
Burnishing $P = 3000$ N	0,46	21	62	30 ÷ 55	- (269 ÷ 969)
Burnishing $P = 4000$ N	0,36	38	80	33 ÷ 66	- (316 ÷ 968)
Burnishing $P = 5000$ N	0,42	6	29	36 ÷ 55	(342 – 1072)
Grinding	0,53	9	27	5 ÷ 26	[289 ÷ (-393)]

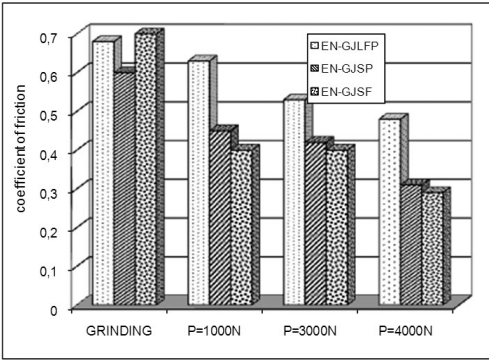
A comparison of test results (Tables 2, 3, and 4) shows that a type of cast iron (especially the form of graphite) affects the condition of the surface layer. In this respect, favorable results were obtained for EN GJS F cast iron – graphite in a globular form.

Figs. 3-4 provide the results of the linear wear and friction coefficient of the cast iron after grinding and burnishing. The tests indicate that better tribological properties (smaller wear and lower friction coefficient) were obtained for the cast iron treated with burnishing than for the cast iron treated with grinding. The explanation for this is a different geometric and physical

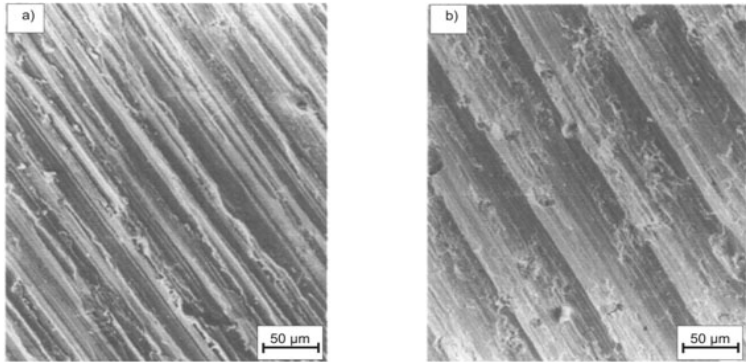
state of the surface layer for each type of treatment. The geometric properties of cast iron after grinding were worse for the surface layer, especially in relation to surface roughness, bearing surface (Tables 2, 3, and 4), and the nature of the surface irregularities. As Fig. 5 illustrates the irregularities of the ground surface (Fig. 5a), compared with the irregularities of the burnished surface (Fig. 5b), have a more "slender" shape, and there are burrs on their outlines. The surface which was burnished has more "streamlined" outlines of irregularities and more directed treatment traces that are the result of plastic deformation of the subsurface layer.



**Fig. 3.** Linear wear of cast iron: EN-GJSP, EN-GJLFP, EN-GJSF in cooperation with  $\text{CuSi}_3\text{Zn}_3\text{Mn}_1$  bronze

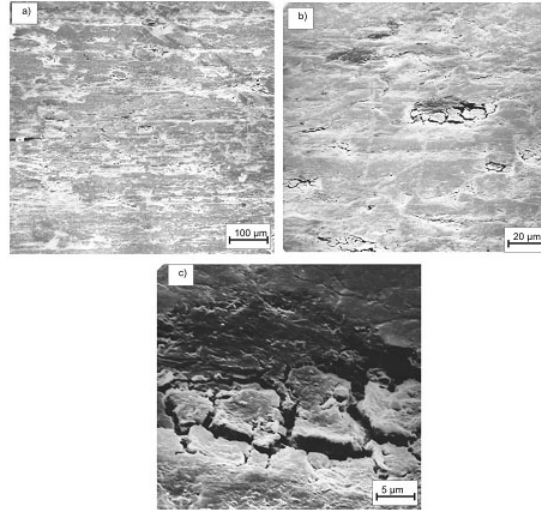


**Fig. 4.** Friction coefficient of cast iron: EN-GJSP, EN-GJLFP, EN-GJSF in cooperation with  $\text{CuSi}_3\text{Zn}_3\text{Mn}_1$  bronze



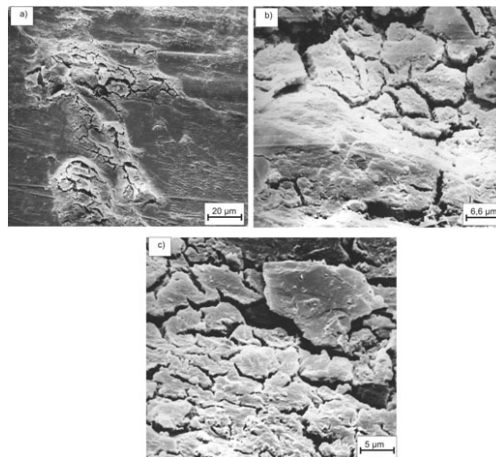
**Fig. 5.** Microphotographies of the geometric structure of technological surfaces: cast iron EN-GJSF: a) after grinding, b) after burnishing with force  $P = 4000 \text{ N}$

Grey cast iron EN-GJL FP after burnishing (the largest wear) had high surface roughness and the smallest bearing surface as compared to the other cast irons. Its wear was affected by the form of graphite, which determined the behavior of the matrix in the process of friction and wear (Fig. 5 and 6). In the process of wear in the areas of flake graphite, the matrix became weak, then it cracked, and finally the matrix particles chipped. Then, as they got between cooperating surfaces, they became abrasive materials, which intensified the wear process and worsened the tribological properties of the friction pair.



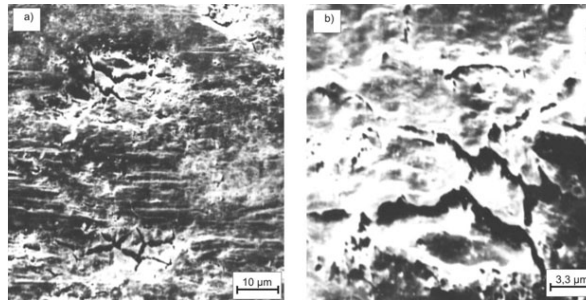
**Fig. 6.** The surface of cast iron EN-GJLFP burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests

A similar phenomenon can be observed in the case of the wear of the cast iron GJS P - Fig. 8. In the subsurface layer where spheroidal graphite occurs, there are microcracks and chipping on the metallic matrix but their size is smaller. The lower wear of the pearlitic spheroidal cast iron, as compared to grey ferritic-pearlitic iron cast, is also caused by differences in the hardness of the metallic matrix before burnishing (for cast iron GJL FP -  $HB_{215}$ , and for cast iron GJS P -  $HB_{310}$ ) - Table 1.

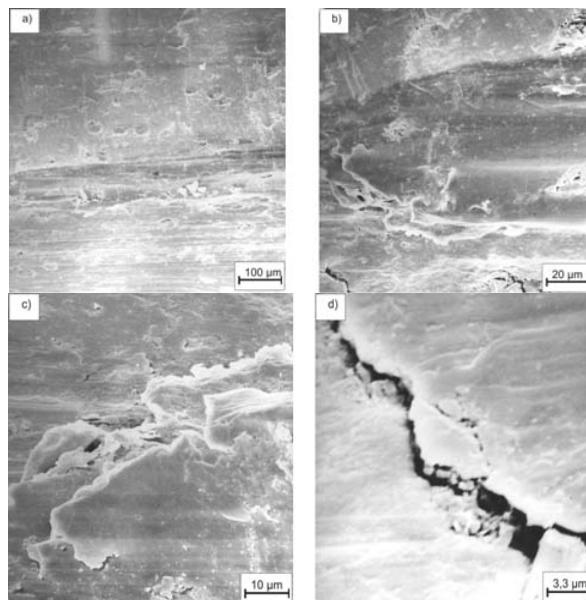


**Fig. 7.** The surface of the cast iron EN-GJLFP burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests

The wear process of the spheroidal ferritic cast iron after burnishing was completely different. This cast iron after burnishing had the lowest roughness and the highest bearing surface  $G_{20}$  and  $G_{50}$  and the largest strengthening of the surface layer (Table 4). In the other cases, the metallic matrix chipped, but in the case of the spheroidal ferritic cast iron, the process of its wear is dominated by the plastic deformation of the tops of irregularities of the subsurface layer. The connection of the adhesive material leads to the piling up of the ferritic matrix, and only subsequently to its partial chipping, as shown in Figs. 9-11.



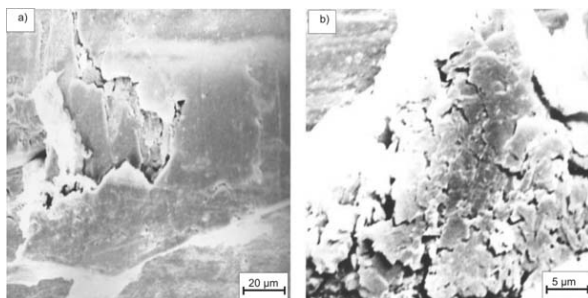
**Fig. 8.** The surface of the cast iron EN-GJSP burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests



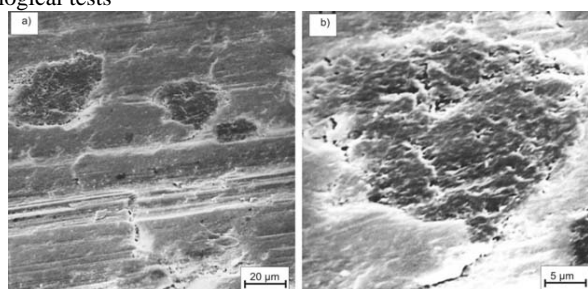
**Fig. 9.** The surface of the cast iron EN-GJSF burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests

Fig. 9a shows the surface of the cast iron sample after burnishing with force of  $P = 4000$  N. On the general plan of the surface, there are traces of graphite just under the surface and the trace in the form of a “cigar” where the soft material (bronze) of the anti-sample was stuck. Observations at higher magnifications (Fig. 9 b, c) confirm that it is an adhesive connection. There are also gaps and areas of concentrated wear products in a form of chipped matrix particles (Fig. 9d). Other details on the friction surface (Fig. 10) are the chippings with the remains of the matrix inside the breach which was formed near spheroidal graphite (Fig. 10a) and the area of cracks and bulges on spheroidal graphite (Fig. 10b). Another detail of the

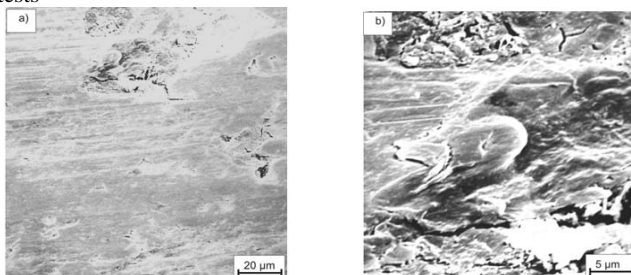
surface is shown in Fig. 11, where exposed graphite separations can be observed. Finally, Fig. 12 illustrates the crack and the wear product in the form of an adhesive connection.



**Fig. 10.** The surface of the cast iron EN-GJSF burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests



**Fig. 11.** The surface of the cast iron EN-GJSF burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests



**Fig. 12.** The surface of the cast iron EN-GJSF burnished by means of pressure rolling with force  $P = 4000$  N after tribological tests

The test results confirmed that the friction-wear properties of cast iron after burnishing are primarily affected by the form of graphite followed by the type of metallic matrix. The preferred form is a globular graphite at which the effective cross-section of the metallic matrix is reduced and the notch does not work. Moreover, spheroidal graphite plays a positive role in the process of friction and wear, because it gets into the friction area and works as a constant friction lubricant, reducing the friction coefficient and wear intensity. It also plays a role in compensating for surface unevenness while decreasing the value of the actual unit pressures. When there is a partial or complete crushing of graphite, a lubricant that improves lubrication conditions collects in the “basins”.

## Conclusions

The tests indicate the following:



1. Burnishing produced a more favorable condition of the surface layer in both the geometric structure and physical properties of the surface of cast irons with respect to cast irons that were subjected to grinding. The following cast irons were studied: spheroidal pearlitic EN-GJSP, spheroidal ferritic EN-GJSF, and grey ferritic-pearlitic EN-GJLFP. The improved tribological properties of the friction pairs included smaller surface roughness according to the parameter  $R_a$ , higher gradients of bearing surface  $G_{20}$  and  $G_{50}$ , greater strengthening, and greater values of compressive residual stresses –  $(\delta_1 + \delta_2)$ .
2. The tribological properties of the tested cast irons in the process of friction depend on the conditions of burnishing, particularly on burnishing force, which has a decisive influence on the amount of energy transferred on a unit of burnished area, and on the shape of the surface layer of a specific geometric surface structure and physical properties of the surface layer.
3. The most favorable tribological properties of the tested cast irons were obtained for the surface burnished with the force of  $P = 4000$  N, producing smaller wear and a lower friction coefficient.
4. It is assumed that the surface after burnishing will shorten the lapping time due to the favorable condition of the surface layer.

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